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ANALYSIS AND MODELING OF SMALL CRACK DETECTIONIN PRESSURIZED FUSELAGES FOR STRUCTURAL HEALTH MONITORING APPLICATIONS (PREPRINT)

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14. ABSTRACT
This effort explores the evolution and characterization of structural cracks in aircraft fuselage structures in which the loads are varying. During flight, an aircraft fuselage skin and structure are subjected to varied cyclic loads, which can cause embedded cracks and other damage features to change their characteristics due to loading effects. The current research uses finite element modeling and experimental techniques to characterize the behavior of cracks under different static loads, with the goal of understanding the interaction of ultrasonic energy with opening-closing crack features. Specimen testing under tensile loads were considered, where crack detection and crack characterization were studied for bonded piezoelectric sensing and guided ultrasonic waves useful in structural health monitoring applications. The results suggest that crack detection and crack sizing accuracy can be impacted by load-induced, crack opening-closure effects, where linear elastic loading of the structure resulted in linear changes in the ultrasonic signal response.

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Analysis and Modeling of Small Crack Detection in Pressurized Fuselages for Structural Health Monitoring Applications

F. Ospina[1], J.L. Blackshire[2], and S.R. Soni[1]

Abstract This effort explores the evolution and characterization of structural cracks in aircraft fuselage structures in which the loads are varying. During flight, an aircraft fuselage skin and structure are subjected to varied cyclic loads, which can cause embedded cracks and other damage features to change their characteristics due to loading effects. The current research uses finite element modeling and experimental techniques to characterize the behavior of cracks under different static loads, with the goal of understanding the interaction of ultrasonic energy with opening-closing crack features. Specimen testing under tensile loads were considered, where crack detection and crack characterization were studied for bonded piezoelectric sensing and guided ultrasonic waves useful in structural health monitoring applications. The results suggest that crack detection and crack sizing accuracy can be impacted by load-induced, crack opening-closure effects, where linear elastic loading of the structure resulted in linear changes in the ultrasonic signal response.

Keywords: Structural Health Monitoring, Crack Opening Displacement, Ultrasound.

1 Introduction

The aviation industry has experienced a remarkable growth since World War II. This growth has been attributed to specific military and commercial design requirements for reliability, maintainability, comfort, safety, speed and many others factors. Requirements for improved passenger comfort, for example, led to the implementation of pressurized cabins by Lockheed in 1943, which has since become a standard practice in the industry.

An unintended consequence of this innovation, however, soon became apparent, when in 1954, the British de Havilland Comet, the largest diameter pressurized fuselage aircraft with windows, had two catastrophic airframe failures resulting in the total loss of the aircraft [Parton and Morozov (1978); Piascik (1999)]. More recently, in April 1988, the Aloha Airlines commercial flight 243 suffered an explosive decompression event during flight, where repeated pressurization cycles and material degradation and fatigue were considered to be major causes of the event [Piascik (1999)].

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An important outcome of these unfortunate accidents involved the identification of pressurization-induced multi-site fatigue damage (MSD) as a critical component of flight safety. In particular, the detection of small cracks at multiple sites in close proximity to each other was identified as a critical need to ensure safe flight operation. As a result, the use of nondestructive evaluation (NDE) inspections occurring at specific time intervals has helped to detect cracks and other damage features in aerospace structures for many decades.

In this research effort, the role of NDE measurements are studied with respect to crack detection in a structure with varying load. The connection of this research with pressurization-induced MSD lies in a new area of damage sensing called integrated structural health monitoring (ISHM), where NDE sensors are permanently attached to a structure, providing real-time detection of cracks while an aircraft is flying. The role of crack-closure due to varying load conditions in the structure become important for ISHM, where the sensing methods can be affected by closure of a crack in compression. Finite element analysis (FEA) models and experimental studies are used in the present effort to understand the effect of load on crack sensing for ultrasonic ISHM sensors, where a linear change in ultrasonic signal response was observed for linear variations in tensile loading of a cracked structure.

2 Linear Elastic Crack Behavior

Numerous experimental and theoretical studies give conclusive evidence of the presence of compressive stresses and crack-closure effects resulting from plastic flow in a material [Parton and Morozov (1978)]. The size of the region covered by the plastic flow depends on the material properties and the loading conditions, but in general, crack-closure near the tip and along the crack length can cause opposing crack faces to contact one another. The addition of static and dynamic loads in a structure can also compress or extend opposing crack face surfaces depending on the type of applied load and its direction. In the present case, tensile loading of a small edge-crack was studied, where the crack opening and closing behavior was of interest along the crack length due to uniaxial loads applied normal to the crack orientation.

The Griffith-Orowan-Irwin concept [Parton (1992)] establishes that the plastic zone is small compared with the crack length but the quasi-brittle region can contribute to closing and hiding small cracks when using conventional ISHM detection techniques. Outside of the plastic zone, the strain, displacement, and stress fields are described by the linear theory of elasticity. Thus, the use of the Griffith-Orowan-Irwin concept makes it possible to preserve the solution of the elasticity theory and it accepts the possibility to consider that once a load is applied, the crack opening displacement (COD) of every pair of points on either side of the crack will hold a linear tendency with increasing load.

3 Crack Dynamics and Finite Element Analysis

COMSOL Multiphysics (V4.2) finite element software was used to estimate the crack opening and closing behavior due to tensile loading of a 3-dimensional dogbone sample geometry (Figure 1). The dogbone sample and geometry are representative of the samples used in the experimental loading experiments described in later sections of the manuscript. The material used in the study was aluminum 2024-T3 (a skin-based aircraft fuselage material), with an overall geometry size of 146 mm long by 30 mm wide by 1.56 mm thick. As depicted in the Figure 1, the sample was tapered in the center to create 6.35 mm wide x 20 mm long gage region for concentrating and localizing stress levels.

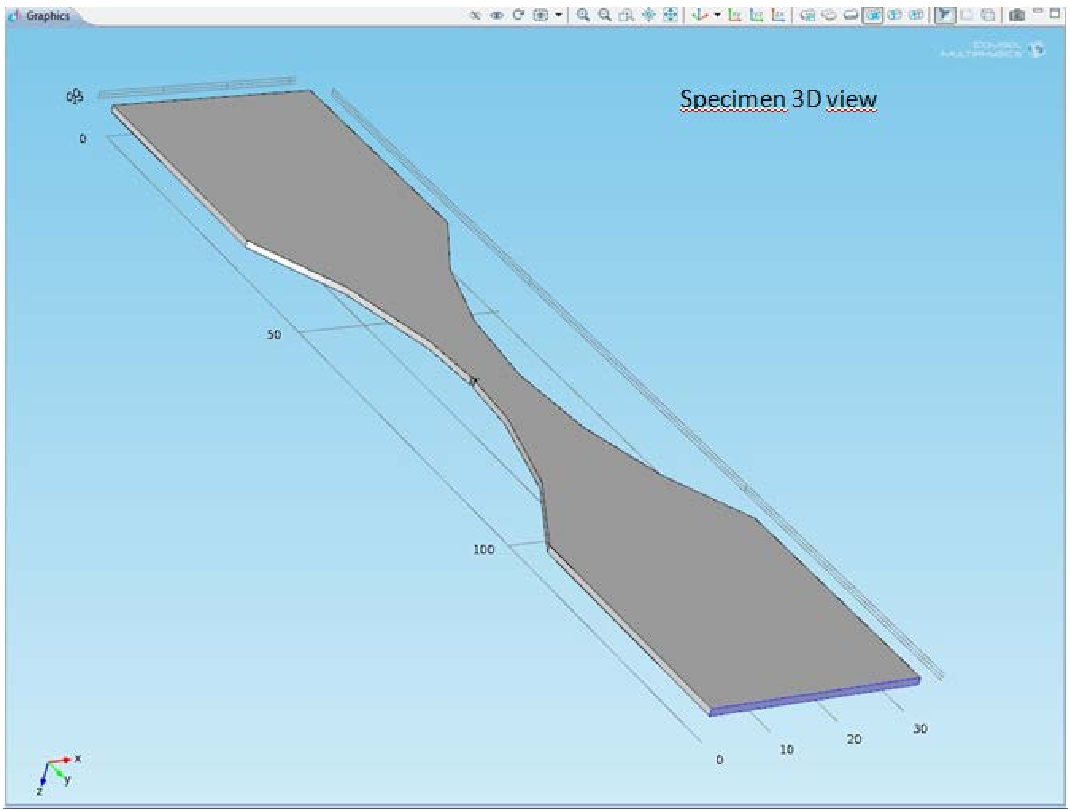

Figure 1: Aluminum 2024-T3 specimen geometry.

Figure 2 (left image) depicts the finite element model for the gage region where a combination edge-notch and crack can be seen on the left of the sample geometry. The notch and crack represent idealized versions (rectangular and planar) relative to the actual notch and crack features described in the experimental section, where overall lengths, sizes, and positions are consistent with the measured values obtained during the fatigue studies. An auto-meshing feature was used in COMSOL to create model nodes and elements as depicted in Figure 2, where increased grid meshing existed in and around the notch and crack feature locations. Figure 2 (right image) provides an example of FEA model results showing stress levels as colored contours in advance of the crack-tip, and geometric opening and separation of the starter notch and crack surfaces with applied tensile loading of the specimen. The model results depicted in Figure 2 are similar to additional model results obtained using tensile load levels between 100 – 400 Psi.

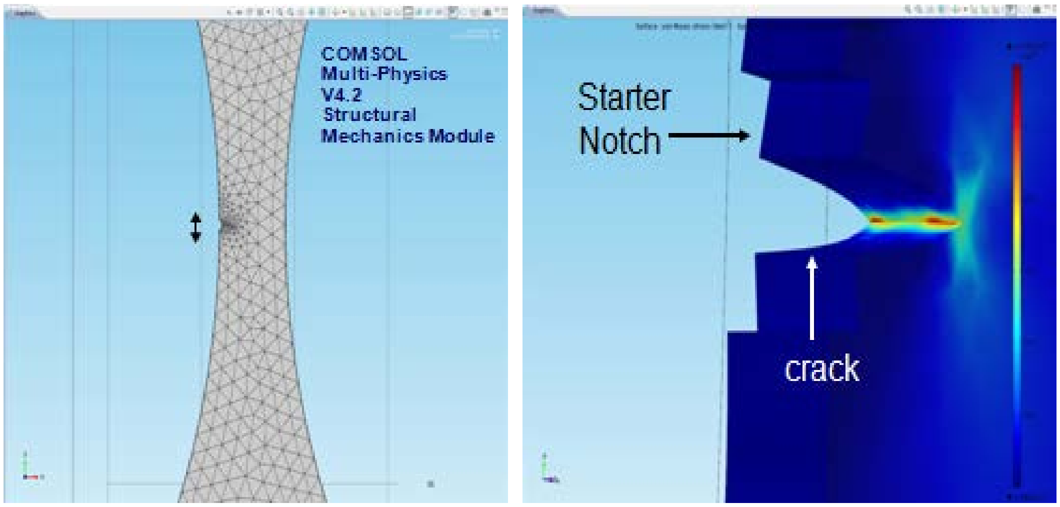

Figure 2: FEA mesh for dogbone specimen (left), and model results of stress concentration and crack opening behavior for applied tensile load (right).

The goal of the COMSOL modeling effort was to estimate crack opening and closing behavior along the crack face for varying load levels. Figure 3 depicts model-based results of crack opening behavior along the crack length for four different load levels. The model-based results depict a logarithmic opening behavior along the crack length with increasing crack opening displacement levels as load levels are increased, which is consistent with theoretical predictions [Riddell, Piascik, Sutton, Zhao, McNeill, and Helm, (1999)].

Additional results are provided in Figure 4, where the crack opening displacement (COD) at the crack root is plotted for increasing load levels between 100 – 400 Psi for two different crack lengths of 922 um and 750 um. Logarithmic and linear fits of the model predictions depicted in Figures 3 and 4, respectively, show excellent R^2 levels. These results show a consistent relationship between increasing the applied load and its effect on the resulting COD for a crack of a certain length. From the modeling point of view, it should be possible to determine the COD for an expected load level, structural geometry, and crack length. This information is valuable for structural health monitoring purposes as will be described in the next sections.

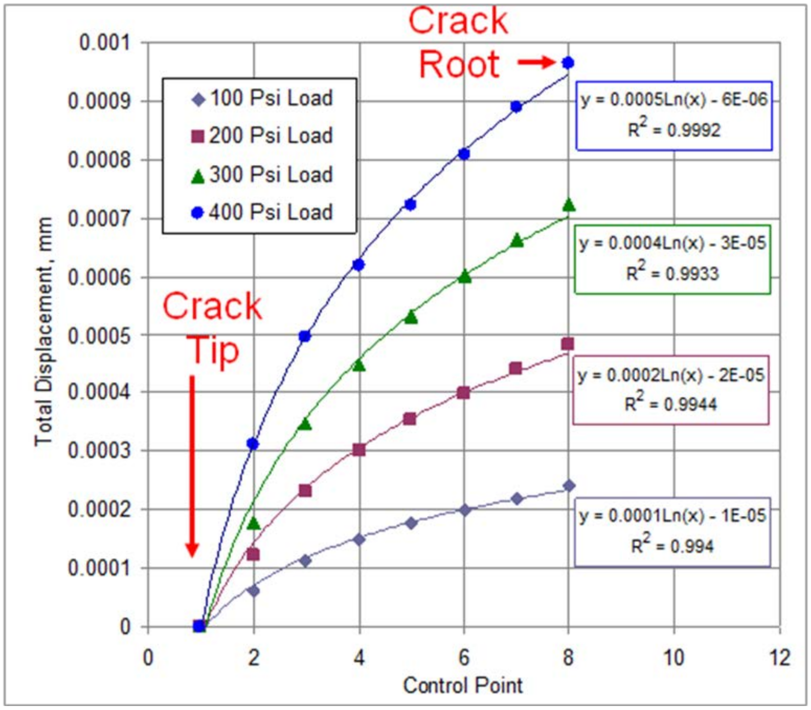

Figure 3: Logarithmic crack opening behavior along the crack face.

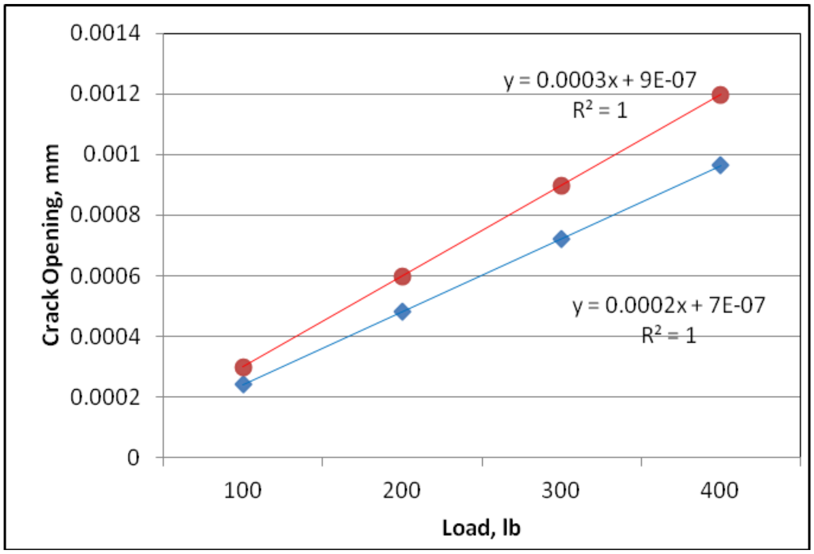

Figure 4: Crack opening behavior for 922 um (top), and 750 um (bottom) crack lengths.

4 Wave Propagation Simulation

A goal of the present research was to understand the effects of crack opening and closing behavior on the detection of cracks using ultrasound ISHM sensing approaches. A combination of models and experiments were used to study the problem, where PZFLEX finite element software was used to study elastic wave propagation and ultrasonic sensing for cracks under different loading states.

The COMSOL mechanical load simulation results described in the previous section were used as an input to the PZFLEX ultrasound models, where an effective crack length was used in PZFLEX based on the crack closure state of the COMSOL model output. The effective crack length represents a reduced crack length relative to the actual/maximum crack length, where crack closure effects cause opposing crack surfaces to make contact, which results in a reduction in the amount of scattered ultrasonic energy. In the PZFLEX models, the crack was modeled as a thin air-gap between the two opposing crack faces surfaces, which represents an idealized case.

Figure 5 provides an example of a typical PZFLEX model result, where a longitudinal ultrasonic wave was launched into the material from the left. The four images correspond to increasing times from the top image to the bottom image, where the propagation of the longitudinal wave from left to right can be seen, along with scattering effects from the crack in the bottom two image frames. The crack represented a small crack case, where the ultrasound wavelength was 5x to 20x larger than the length of the crack.

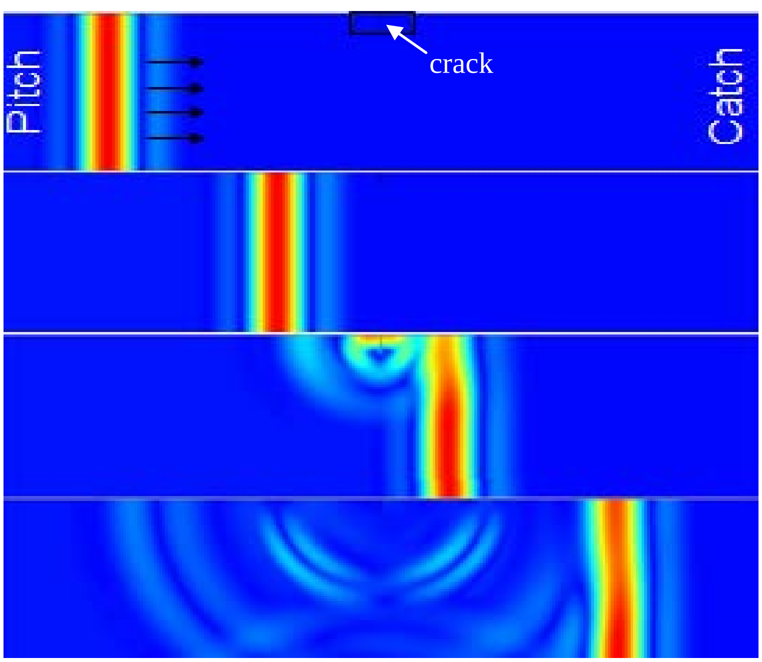

Figure 5: PZFLEX ultrasonic model results depicting ultrasonic wave propagation from left to right and crack scattering at four times.

Simulated ultrasonic signals were collected on the right side of the material, which represent a pitch-catch sensing arrangement. This signal information was used to study ultrasonic scattering from the crack for variations in load and effective crack length as predicted in the COMSOL models. The percent signal loss due to crack closure effects is depicted in Figure 6, where a linear relationship was observed between the normalized effective crack length and the percent signal reduction.

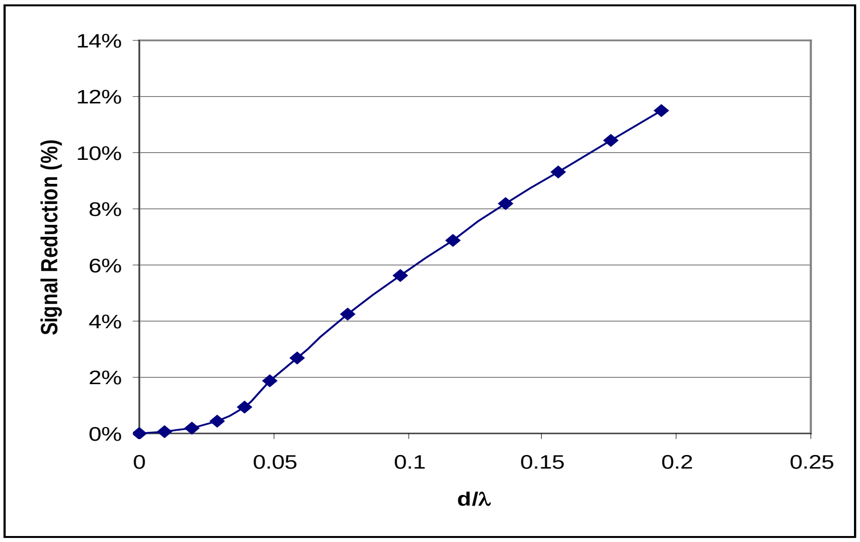

Figure 6: PZFLEX ultrasonic signal reduction due to normalized effective crack length variations.

5 Sample Testing and Experimentation

A series of cyclic tensile loading tests were conducted to grow small edge cracks in the aluminum dogbone sample geometry depicted in Figure 1. As previously discussed, the goal was to generate small cracks with lengths below 1 mm. A miniature USB camera with a 300x magnification was used to track in real time the initiation and growth of the cracks from starter notch positions in the center of the gage region. Figure 7 (left image) depicts a dogbone sample in the MTS load frame and the in-situ camera system being adjusted.

An example of an image taken with the USB camera system is also depicted in Figure 7 (right image), where a 922 um long crack has been generated and is being subjected to a 351 Lb load level with the MTS load frame. Approximately 650 microns of the crack is shown in the image field, where the starter notch is located just to the left of the image frame, and the crack tip extends out of the frame towards the right. As depicted in the figure, the crack is very irregular in shape, where noticeable crack opening conditions can be observed. Figure 8 depicts crack opening measurements at 13 points extracted from the crack image field in Figure 7, where a exponential relationship crack opening behavior exists from the root to the tip.

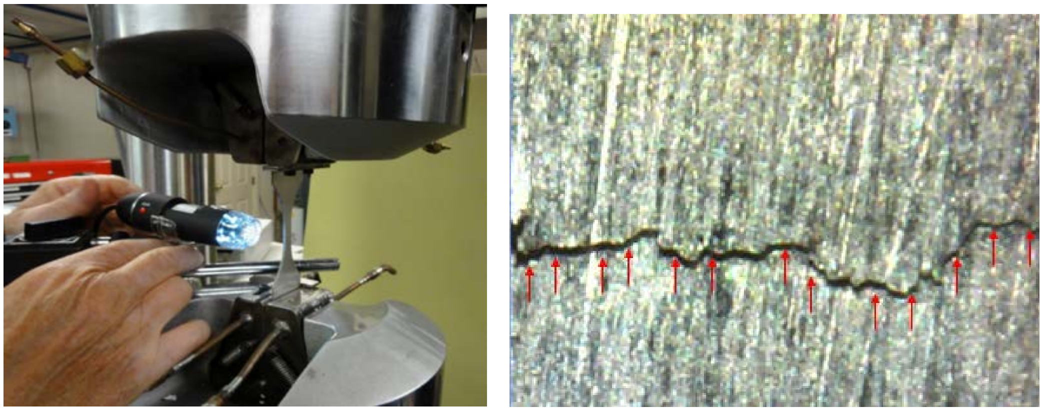

Figure 7: In-situ crack opening imaging and accelerated fatigue testing (left image), and in-situ crack image for 922 um edge-crack subjected to 350 lb tensile load (right image).

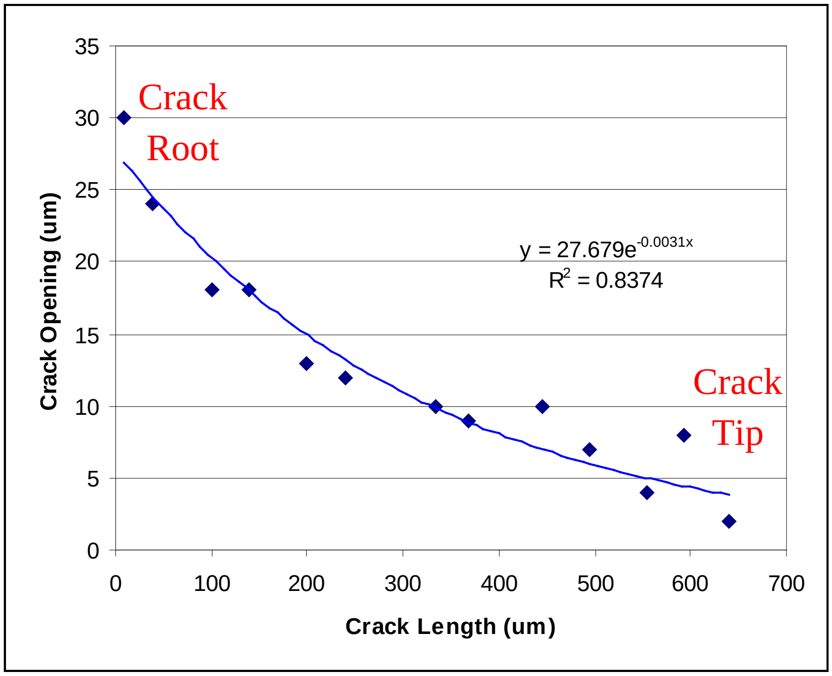

Figure 8: Exponential crack opening behavior along the crack face for crack positions depicted in Figure 7.

In addition to the in-situ microscopy images, a series of ultrasonic signals were captured for two pairs of bonded piezoelectric sensors, which have recently been used in ISHM aerospace applications for crack detection [Na and Blackshire (2010); Blackshire, Martin, and Cooney (2006)]. The sensors included a 6mm diameter round piezoelectric disk, which generates guided omnidirectional Lamb waves in the thin aluminum material system, and a 3mm x 7mm rectangular interdigitized piezoelectric transducer (IDT) that generates surface waves at 3.1 MHz. As depicted in Figures 9 and 10, the sensors were arranged in a pitch-catch sensing arrangement, where a pair of Lamb wave sensor disks were placed on the front side of the specimen, and a pair of IDT sensors were placed on the back of the specimen. Ultrasonic signals were collected for increasing specimen load levels.

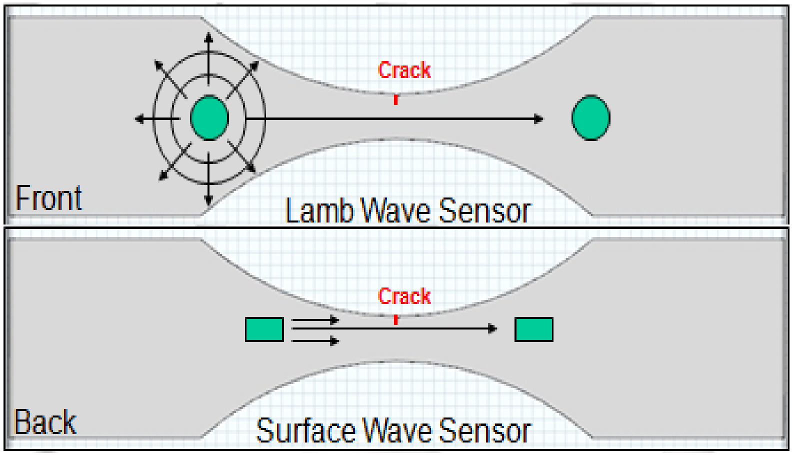

Figure 9: In-situ ultrasound Lamb wave sensor and surface wave sensor configurations.

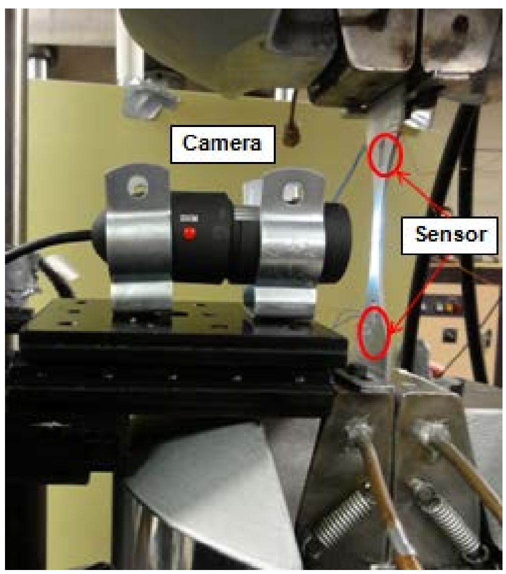

Figure 10: In-situ piezoelectric sensor and imaging system in MTS load frame.

As described previously, a goal of the current effort was to study the impact of crack closure states on the ultrasound signals captured using bonded piezoelectric sensor configurations. As depicted in Figure 11, a noticeable change in the visible crack opening and closure states of a small crack were observed in the current study for material systems and load states typically found in an aerospace system. An interesting observation is depicted in the 0 lb case of Figure 11, where the crack is very difficult to observe visibly even at 300x magnification levels. As tensile load levels are increased, however, the crack is easily observed, with a systematic increase in crack opening behavior with load.

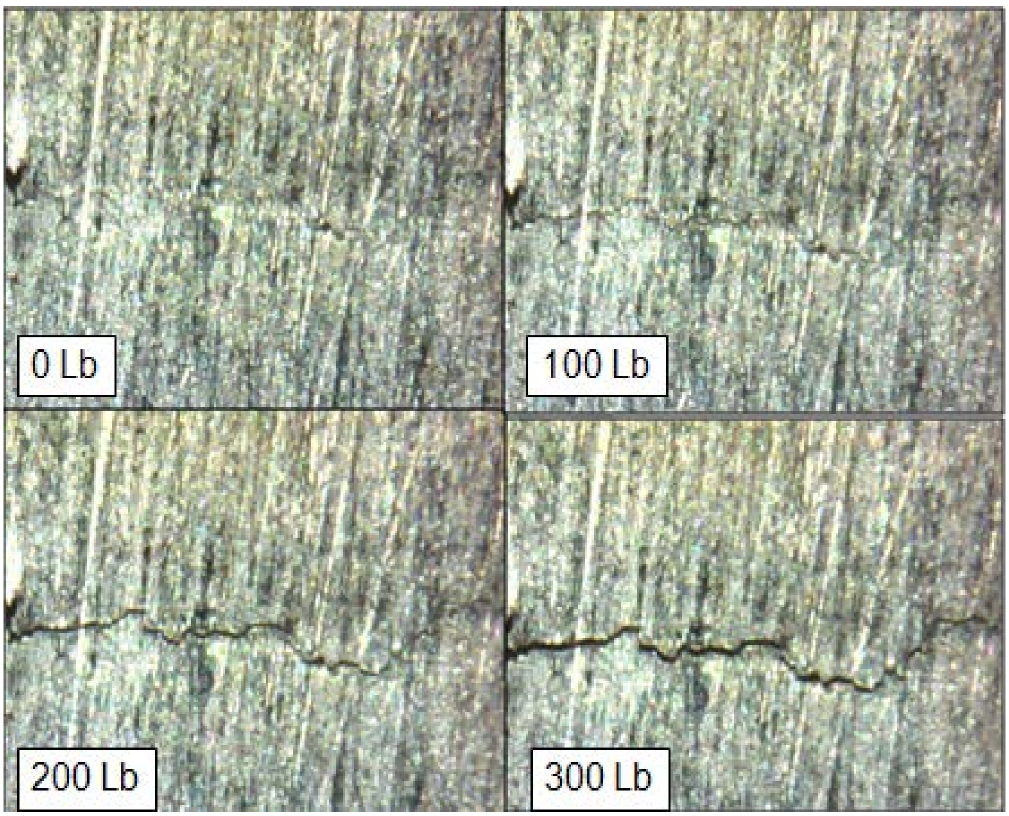

Figure 11: In-situ crack opening images for different loading level configurations.

Representative ultrasonic pitch-catch signals are depicted in Figure 12 (left plot), where the IDT surface acoustic wave signals are plotted. A comparison of signals for increasing load show a systematic shift in time and change in amplitude as load levels are varied and crack closure states change. The observed signals can be explained using the PZFLEX model predictions described previously, were a subtle change in phase and amplitude can be seen in the ultrasonic waves in Figure 5 due to scattering from the crack. As the effective crack length shortens due to crack closure effects, the scattering effects are reduced, and signal changes are reduced in phase and amplitude.

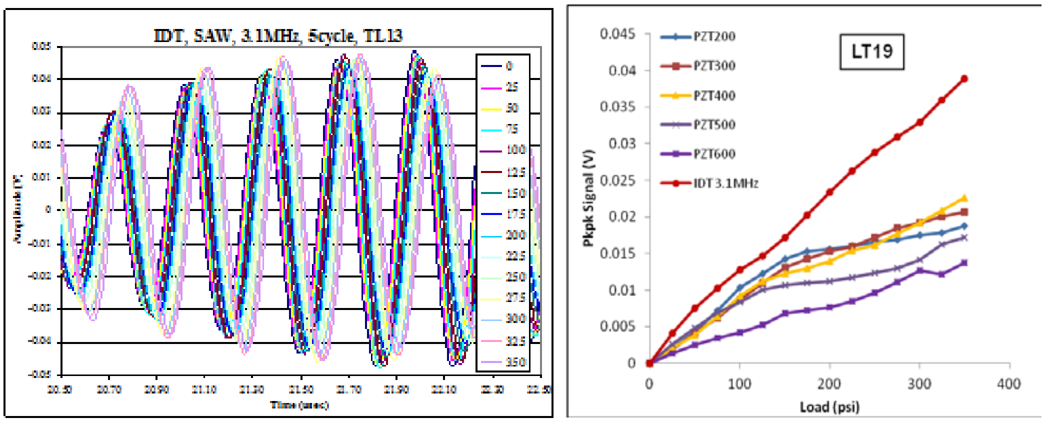

Figure 12: In-situ bonded piezoelectric sensor signals for increasing load (left plot), and peak-to-peak ultrasonic signal amplitudes vs tensile loads (right plot).

A comparison of the peak-to-peak amplitude change in signal response is depicted in Figure 12 (right plot) for the IDT surface wave sensor operated at 3.1 MHz, and for the Lamb wave sensor operated at five different frequencies from 200-600 kHz. A systematic change in amplitude can be seen in each case, with the IDT surface wave sensor showing the maximum sensitivity to changing crack closure and load states. The surface wave sensor operates in a more directional beam nature, and involves shorter wavelengths, which both provide an opportunity to enhance scattering processes with short cracks below 1 mm in length.

5 Conclusions

The evolution and characterization of structural cracks in aircraft fuselage structures with varying loads is of critical importance for flight safety. In this effort the crack opening and closing behavior of an edge crack was studied in a thin aluminum skin material using forward models and experimental validation studies. Crack opening displacement levels were measured in-situ using a digital microscope system under static loads, where crack opening behavior showed trends which were in agreement with linear elastic theory and with numerical model predictions. In-situ ultrasonic measurements of crack scattering behavior was also studied using Lamb and Rayleigh wave sensor pairs, where systematic reductions in pitch-catch signal level were obtained for increasing load levels. The results suggest that crack closure effects near the crack tip and along its length cause the crack faces to make contact, which reduces ultrasonic scattering levels, leading to potential variations in crack detection sensitivity and crack sizing reliability.

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